Fermi National Accelerator Laboratory

FERMILAB-Pub-89/203-A
September 1989

COSMIC NONTHERMAL ELECTROMAGNETIC BACKGROUND FROM AXION DECAYS IN THE MODELS WITH LOW SCALE OF FAMILY SYMMETRY BREAKING

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Abstract

The existence of cosmic nonthermal electromagnetic background, accessible to astronomical searches, is predicted in the framework of quantum flavordynamics with low ($\sim 10^6 \div 10^7$GeV) scale of family symmetry breaking. The background is generated in $\gamma\gamma$ decays of axions, arising from $\nu_\tau \to \nu_\mu \alpha$ decay of ν_τ with mass of few keV at $t \lesssim 10^{10}$ s and from $\nu_\mu \to \nu_e \alpha$ decay of $50 \div 100$ eV ν_μ at $t \leq 10^{16}$s in the Universe. Possible ionizing effect of this background and its possible relationship with spectral distortions of the microwave thermal background are considered.

Submitted to the Soviet Journal of Nuclear Physics.

The unified physical description of all the main types of dark matter particles (the prediction of the hierarchy of neutrino masses and lifetimes, of the energy scale v_{PQ} of axion interactions and of its coupling constants) as well as the prediction of rather definite relationship between the parameters of these particles is the specific feature of the local gauge theory of broken family symmetry, being evolved recently in [1-3]. The existence of axion is related in this theory to the breaking of global $U(1)$ symmetry, being intrinsically inherent to the considered scheme at the natural and self consistent choice of the potential of Higgs fields, breaking the symmetry of families. Such an axion α turns to be simultaneously familon and Majoron of the singlet type, what results in the prediction of flavor nondiagonal transitions with axion emission both for quarks and leptons, and for massive neutrinos. The properties of this axion are close to the properties of so called "hadronic" axion with strongly suppressed coupling with first generation quarks and leptons in the tree approximation. The account for the contribution into these couplings of αgg interaction, induced by triangle fermion loop diagrams, leads to the enhancement of diagonal α interactions with light quarks and determines the mass of axion $\sim \Lambda^2_{QCD}/v_{PQ}$. Similar diagrams induce $\alpha\gamma\gamma$ interaction, leading to $\alpha \to \gamma\gamma$ decay with the lifetime [4]

$$\tau(\alpha \to \gamma\gamma) = \frac{2^8\pi^3}{N_g^2\alpha_{em}^2}\frac{1}{c^2_{\alpha\gamma\gamma}}\frac{v^2_{PQ}}{m^3_\alpha} \tag{1}$$

where N_g is the number of quark colors and $c_{\alpha\gamma\gamma}$ is the axion electromagnetic coupling constant. It is seen from Eq. (1), that the effects of axion decay are most significant at the maximally low possible scale v_{PQ} of family symmetry breaking. Possible features of these effects in cosmology are discussed in the present note.

The lower estimation of the scale v_{PQ} follows from the analysis of the effect of energy losses due to axion emission on the evolution of red supergiants: $v_{PQ} > 10^6$ GeV [4-6]. An estimation of approximately same order of the magnitude goes from the experimental constraints on the probability of rare axion decays such as $\mu \to e\alpha$,

$\tau \rightarrow \mu\alpha$, $B \rightarrow K(K^*)\alpha$, $K \rightarrow \pi\alpha$, etc. [3]. On the other hand, the estimation of possible axion energy losses, following from the analysis of neutrino signal, preceeding the burst of Supernova SN 1987A, excludes the range of v_{PQ} values 10^7GeV $< v_{PQ} <$ 10^{10}GeV [7]. Meanwhile the analysis of the dependence of the predicted dark matter density on v_{PQ} shows, that in the range $v_{PQ} \sim 10^6 \div 10^7$ GeV rather nontrivial cosmological scenario of cosmological dark matter evolution is realized, including [3]:

a) the dominancy of ν_τ with the mass of the order of few keV in the period $10^8 \div 10^{10}$s, finishing by $\nu_\tau \rightarrow \nu_\mu \alpha$ decay

b) formation of the large scale structure of the Universe by muon neutrinos with the mass $50 \div 100$ eV and the lifetime $10^{15} \div 10^{16}$s relative to $\nu_\mu \rightarrow \nu_e \alpha$ decay

c) dominancy in the modern cosmological inhomogeneities of nonrelativistic axions from ν_τ decay and the presence several times greater by density homogeneous dark matter, maintained by ν_e and α from ν_μ decay.

The existence of $\alpha \rightarrow 2\gamma$ axion decay leads in the framework of this scenario to the prediction of nonthermal electromagnetic background. As we will show, the presence of such background at $Z \leq 10^3$ turned to prevent the recombination of the matter, decreasing the predicted small scale anisotropy of relic radiation, and the existence of such background in the modern Universe provides additional opportunity to test the theory [1-3] in astronomical observations.

Turning to consideration of these effects, let's note, that for considered range of values $v_{PQ} \sim 10^6 \div 10^7$ GeV the predicted density of primordial axion/coherent oscillations and the density of primordial thermal axions are small, so that the main sources of axions in the Universe are the decays $\nu_\tau \rightarrow \nu_\mu \alpha$ at $t \leq \tau(\nu_\tau)$ and then at $t \leq \tau(\nu_\mu)$ $\nu_\mu \rightarrow \nu_e \alpha$ decays. The mass of axion is $m_\alpha \sim$ few eV and since $m_{\nu_\mu}(m_{\nu_\tau}) \gg m_\alpha$, axions from these decays remain for long time relativistic. Axions from ν_τ decay turn then nonrelativistic and go into the modern inhomogeneities and axions from ν_μ decay may remain semirelativistic even at present time.

Consider now spectra of photons from decays of axions, being the products of ν_τ and ν_μ decays, respectively. The photon spectrum for the decays $\nu_\tau \to \nu_\mu \alpha(\alpha \to 2\gamma)$ is easily calculated, since axions are cooled to the present time and their momenta may be put equal to zero. The differential probability for the decay of such axions is given by $\frac{d\Gamma}{dk} = \frac{N_g^2 \alpha_{em}^2}{2^8 \pi^3} \left(\frac{C_{a\gamma\gamma}}{C_{agg}}\right)^2 \frac{m_a^5}{\Lambda_{QCD}^4} \delta(k_o - k)$ where $k_o = \frac{1}{2} m_\alpha$, and k is the photon energy. Then the spectrum of photons in the expanding Universe has the form [8]

$$\frac{dn_\gamma}{dt} = 2n_o \Gamma N \frac{k^{N-1}}{k_o^2} exp\left[-\Gamma\left(\frac{k}{k_o}\right)^N t_U\right] \theta(k_o - k) \qquad (2)$$

Here N is determined by the law of the cosmological expansion, determined in its turn by the cosmological equation of state. If decay takes place at the stage of relativistic particles dominancy ($p = \epsilon/3$) $N = 2$, and the nonrelativistic, dust-like stage ($p = 0$) $N = 3/2$. The case $N = 2$ will be further of interest for us, since it corresponds to the stage of dominancy of relativistic products of ν_τ and ν_μ decays. In this case one has from Eq. (2)

$$\frac{dn_\gamma}{dk} = 4n_o \cdot 1.1 \cdot 10^{-22} \left(\frac{m_a}{3eV}\right)^5 \frac{k}{k_o^2} exp\left[-1.1 \cdot 10^{-22} \left(\frac{m_a}{3eV}\right)^4 \left(\frac{k}{k_o}\right)^2 t_U\right] \quad , \qquad (3)$$

where $n_o = \frac{3}{11} \cdot 400\ \mathrm{cm}^{-3} = 110\mathrm{cm}^{-3}$, $t_U \approx 3 \cdot 10^{17}$ s is the age of the Universe. For $k < k_o$ and $\Gamma t_U \ll 1$ one obtains $\Gamma\left(\frac{k}{k_o}\right)^2 t_U \ll 1$.

The situation is different, when one considers $\nu_\mu \to \nu_e \alpha(\alpha \to 2\gamma)$ decays. ν_μ with the mass $50, \div 100$ eV decay at $\tau \sim 10^{15} \div 10^{16}$ s, so that axions with the mass $\sim$ few eV are semirelativistic at present time and to estimate the nonthermal background from their decays we must use the differential probability of axion decay in flight, given by

$$d\Gamma(\alpha \to 2\gamma) = 1.1 \cdot 10^{-22} \left(\frac{m_a}{3\mathrm{eV}}\right)^5 \cdot \frac{m_a}{\varepsilon\omega} dk \quad ,$$

where k is photon momentum, and ω is axion momentum. Spectrum of photons from decays of monochromatic axions with the momentum ω has flat "table-like" form and is in the interval

$$\frac{m_\alpha^2}{2(\varepsilon+\omega)} < k < \frac{m_\alpha^2}{2(\varepsilon-\omega)} \quad , \varepsilon = \sqrt{\omega^2 + m_\alpha^2} \quad ,$$

but since axions from $\nu_\mu \to \nu_e \alpha$ decays, taking place in different time, experience different redshift, photon spectrum is deformed respectively so that the photon concentration decreases with the increase of photon energy. The total number density of photons is given by

$$n_\gamma = \int\int n_o \frac{2t}{\tau_{\nu_\mu}} \frac{\omega}{\omega_o^2} exp\left[-\frac{t}{\tau_{\nu_\mu}}\left(\frac{\omega}{\omega_o}\right)^2 \cdot \Gamma\right] \cdot \frac{m_\alpha}{\varepsilon} dt d\omega \tag{4}$$

where $n_o = 2 \cdot \frac{3}{11} \cdot 400\ \mathrm{cm}^{-3}$. One obtains from (4)

$$n_\gamma = 2n_o \left(\frac{8 \cdot 10^{15}\mathrm{s}}{\tau_{\nu_\mu}}\right)^{1/2} \cdot \frac{1}{\omega_o} \cdot 1.1 \cdot 10^{-22} \left(\frac{m_\alpha}{3eV}\right)^6 \sqrt{\frac{\pi}{2}} \cdot t_U^{3/2} \quad . \tag{5}$$

Into the obtained total number density of photons the main contribution comes from the spectral range $\frac{m_\alpha^2}{2m_{\nu_\mu}}\left(\frac{t_U}{\tau_{\nu_\mu}}\right)^{1/2} < k < \frac{m_{\nu_\mu}}{2}\left(\frac{\tau_{\nu_\mu}}{t_U}\right)^{1/2}$. Taking for numerical estimation the optimal parameters of the cosmological model of unstable ν_μ with $m_{\nu_\mu} = 60$ eV and $\tau_{\nu_\mu} = 8 \cdot 10^{15}$ s [9], let's calculate the amount of background photons predicted in the optical range (4000 Å÷7600 Å). Numerical estimates show, that $n_\gamma = 8 \cdot 10^{-4}\ \mathrm{cm}^{-3}$, being compatible with the experimental data [10] $n_\gamma \sim 10^{-3}\mathrm{cm}^{-3}$ for $m_\alpha < 3.3$ eV. To estimate the background at shorter wavelengths one obtains with the use of Eq. (4) integrated overt

$$n_\gamma = \int n_o \cdot 2\left(\frac{\tau_{\nu_\mu}}{8 \cdot 10^{15}\mathrm{s}}\right) \frac{\omega_o^2}{\omega^4} \cdot 1.1 \cdot 10^{-22} \left(\frac{m_\alpha}{3eV}\right)^6 \cdot exp\left[-t_U \left(\frac{\omega}{\omega_o}\right)^2 \left(\frac{8 \cdot 10^{15}\mathrm{s}}{\tau_{\nu_\mu}}\right)\right] d\omega \quad . \tag{6}$$

In the interval 6.47 eV $< k <$ 7.63 eV, what corresponds to the wavelengths 1610 Å$< \lambda <$ 1950 Å, the photon flux is predicted $\sim$ 800 photon/s cm$^2\cdot$ ster $\cdot$ Åfor $m_\alpha = 3.3$ eV. This result is compatible with the data on the observed flux in this range (900 ± 150 photons/s $\cdot$ cm^2 $\cdot$ ster$\cdot$ Å) [11]. One can show by similar estimations, that the predicted intensity of electromagnetic background do not contradict experimental data in other ranges $1450 \div 1780$ Å (550 ± 150 photons/s $\cdot$ cm^2 $\cdot$ ster $\cdot$ Å) and $1700 \div 2420$ Å (≤ 1300 photons/s $\cdot$ cm^2 $\cdot$ ster $\cdot$ Å) [11].

Concerning the background with the spectrum, given by the Eq. (3), one notes, that the maximal energy of such photons is $k = m_\alpha/2$ and for $m_\alpha = 3.3$ eV such photons are in the infrared part of the electromagnetic spectrum with the total amount

$$n_\gamma \approx n_o \cdot 10^{-22} t_U \approx 10^{-2}\mathrm{cm}^{-3} \quad , \tag{7}$$

being by the two orders of the magnitude smaller than experimental constraints (see cf [10]).

The above estimations put rather stringent constraint on the mass of axion $m_\alpha <$ 3.3 eV and, correspondingly, on the scale of the family symmetry breaking $v_{PQ} >$ $3.5 \cdot 10^6$ GeV.

Using the obtained expressions, let's estimate now the influence of hard photons from axion decays on the course of recombination (such photons are predominantly the products of the decays $\nu_\tau \to \nu_\mu \alpha(\alpha \to 2\gamma)$). Take for definiteness the following values of parameters: $m_{\nu_\tau} = 1.2$ keV; $m_{\nu_\mu} = 60$ eV; $m_\alpha = 3.3$ eV; $v_{PQ} = 3.5 \cdot 10^6$ GeV. Then

$$\begin{aligned} \tau_1(\nu_\tau \to \nu_\mu \alpha) &= \frac{g^2_{\tau_\mu} \cdot m_{\nu_\tau}}{16\pi} = 8 \cdot 10^9 \mathrm{s} \\ \tau_2(\nu_\mu \to \nu_e \alpha) &= 8 \cdot 10^{15} \mathrm{s} \end{aligned} \tag{8}$$

To estimate the ionization of the matter, photons with momentum $k > k_L =$ 13.6 eV, arising from decays of axions with $\varepsilon > 13.6$ eV are to be considered only. With the account for this restriction the expression for the probability of axion decay takes the form:

$$\Gamma'(\alpha \to 2\gamma) = \int_o^\omega \frac{d\Gamma}{dk} \frac{m_\alpha}{\varepsilon \cdot \omega} dk + \int_{k_L}^{\omega - k_L} \frac{d\Gamma}{dk} \frac{m_\alpha}{\varepsilon \cdot \omega} dk \quad , \tag{9}$$

where the second term arises, since in the interval $k_L < k < \omega - k_L$ we must take into account two photons, accessible to ionize the matter. One has

$$\Gamma'(\alpha \to 2\gamma) = 1.1 \cdot 10^{-22} \left(\frac{m_\alpha}{3eV}\right)^5 \left[\frac{2m_\alpha}{\varepsilon} - \frac{2k_L m_\alpha}{\varepsilon\omega}\right] 1/s \tag{10}$$

For the accepted values of parameters (8), neglecting, generally speaking, rather long transitional stages of the change of the equation of state of the Universe, we shall assume for a crude estimate the relativistic expansion law until $\omega \sim 40$ eV at $t = t'$ and then the nonrelativistic expansion, decreasing the axion energy down to 13.6 eV to the time t'':

$$\left(\frac{600}{40}\right)^2 = \frac{t'}{\tau_1}, \quad t' = 1.9 \cdot 10^{12}\mathrm{s}, \quad \left(\frac{40}{13.6}\right)^{3/2} = \frac{t''}{t'}, \quad t'' = 10^{13}\mathrm{s}$$

In the assumed approximation of the instantaneous change of the equation of state nonrelativistic expansion lasts until $t = \tau_2 = 8 \cdot 10^{15}$s, and then due to $\nu_\mu \to \nu_e \alpha$ decays the expansion follows again the relativistic law. The period $t = 8 \cdot 10^{15}$s corresponds to the redshift $Z + 1 = 7$. According to the big bang theory [10] recombination starts at $Z = 1500$, so that $t_{\mathrm{rec}} = \tau_2 \left(\frac{7}{1500}\right)^{3/2} = 2.5 \cdot 10^{12}$s.

Let's calculate the amount of hard photons with the energy, exceeding $k_L = 13.6$eV.

$$n_\gamma = \int\int n_o \frac{2t''}{\tau_1} \left(\frac{t}{t'}\right)^{4/3} \frac{\omega}{\omega_o^2} exp\left[-\left(\frac{\omega}{\omega_o}\right)^2 \frac{t'}{t} \cdot \left(\frac{t}{t'}\right)^{4/3}\right]$$
$$\cdot 1.1 \cdot 10^{-22} \left(\frac{m_\alpha}{3eV}\right)^5 \cdot \frac{2m_\alpha}{\varepsilon}\left(1 - \frac{k_L}{\omega}\right) d\omega dt \quad . \tag{11}$$

It follows from Eq. (11), that $r_\gamma \geq 2.8 \cdot 10^{-11}$ at $Z < 1400$, where $r_\gamma = n_\gamma / n_T$ and n_T is the number density of thermal relic photons.

Compare now ionization and recombination rates. The ionization cross section is $\sigma_i = \frac{6 \cdot 10^{-17}}{(\nu/1eV)^3}\mathrm{cm}^2$, where ν is the energy of the ionizing photon. The recombination cross section is $\sigma_2 = \frac{2 \cdot 10^{-5}}{(\nu/1eV)(v/1\mathrm{cm/s})^2}\mathrm{cm}^2$, where ν is the energy of emitted photon and v is the relative velocity of electron and proton.

Comparing the rate of recombination A_r with the rate of ionization A_i it is easy to find that $A_i > A_r$ for $500 < t < 1400$, but, since the amount of ionizing photons is only few percent of the amount of baryons, these photons can ionize the fraction of atoms, not exceeding the amount of photons. However, the optical depth for relic photons $\sigma_T n_e ct$, where $\sigma_T = 0.66 \cdot 10^{-24}\mathrm{cm}^2$ is the Thomson cross section and n_e is the concentration of ionized electrons, and it turns to be ~ 2, what may slightly decrease the predicted anisotropy of the thermal background (see cf [9] and refs. therein).

There is another possible effect of these backgrounds. The predicted large amount of hard photons ($n_\gamma \approx 10^6 n_B$, where n_B is the baryon concentration) from $\nu_\mu \rightarrow \nu_e \alpha(\alpha \rightarrow 2\gamma)$ decays can ionize all the matter and prevent recombination until the photon energy will be redshifted below the threshold. If recombination starts at $Z \sim 1$, the emitted photons, being redshifted down to the energy 7.4 eV, will give the observed peak in the ultraviolet background [12]. However such an explanation of the data on the ultraviolet background assumes the possibility of the recombination of the matter at $Z \sim 1$ and do not take into account the ionizing radiations of QSO and bright galaxies, what needs special investigation.

Finally, the estimation of the energetics of the radiation from axion decays shows, that its modern energy density may reach about 20% of the energy density of the thermal electromagnetic background. The transformation of the nonthermal background from axion decays owing to its interaction with dust may result in the distortion of the Wien part of the thermal microwave background. The possibility of such a description of the observational claims [13] on the existence of such distortions also needs special treatment. The dependence of the anisotropy of microwave background on the frequency [14] may arise in this case.

We are grateful to V. K. Dubrovich for valuable discussions and comments. This work was completed at Fermi National Accelerator Laboratory under the auspices of NASA grant NAGW-1340.

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